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## Construction of a Hyperspectral Imager using 3D-printed and off-the-shelf components

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# **Construction of a Hyperspectral Imager using 3D-printed and off-the-shelf components**

An Honors Thesis submitted in partial fulfillment  
of the requirements for the Honors Program in Mechanical Engineering

By

Joshua Moorhouse

Spring 2020

Mechanical Engineering

College of Engineering

The University of Arkansas

## **Acknowledgments**

I am greatly appreciative of Dr. Chevrier, Dr. Roe, Connor Heo, and Brandon Wallace. Each of these individuals contributed greatly to the development and future work of this project. I'd also like to thank the Mechanical Engineering Department and the Arkansas Center for Space and Planetary Sciences for giving us the ability to conduct this project.

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# Introduction

## Background

Hyperspectral imaging has been used in many forms for decades to uncover new information and advance science [1]. Hyperspectral imaging reveals unique characteristics about an object by viewing the wavelengths of light being emitted off that object. Passing the light through a type of grating splits the light into its individual wavelengths for observation by a camera. The resulting image is a spectrogram of that light. This can be done in the visible, UV, infrared, and near-infrared spectra. A spectrogram shows emission lines that relate to distinct wavelengths, usually displayed on a black background. An example spectrogram is shown in Figure 1. The hyperspectral images are created by viewing a spectrogram of the object for each pixel of the object.

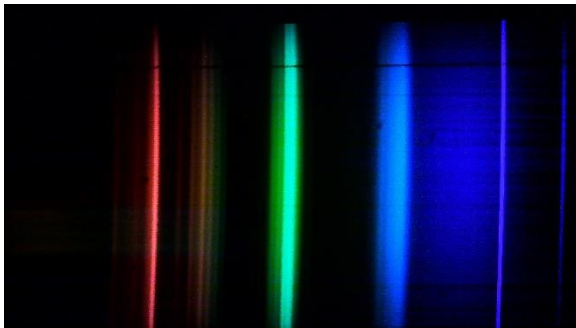


Figure 1: Example spectrogram

The objective of this project was to create a working camera that could display spectrograms in the visible spectrum. Hyperspectral images could then be created using these spectrograms. The camera's design would be modular and provide the groundwork to create a camera able to work in the infrared and near-infrared spectra. To create hyperspectral images this camera would use a push-broom method approach. The camera would create spectrograms for

each pixel row along the imaged object. These spectrograms would be then be used to create the hyperspectral image. Much of this project is based on a similar project undertaken by a team in Norway led by F. Sigernes [2].

## Theory

The primary component used in the imager is the diffraction grating. This piece takes the incoming light and breaks it into its individual wavelengths. This experiment uses a transmission style diffraction grating, which allows light to pass through it after the light is broken up.

The grating works because it has many lines drawn onto it, hundreds of lines per millimeter. The lines break the incoming light into its fundamental wavelengths and then allows the light to pass through. This can be seen in Figure 2 [3].

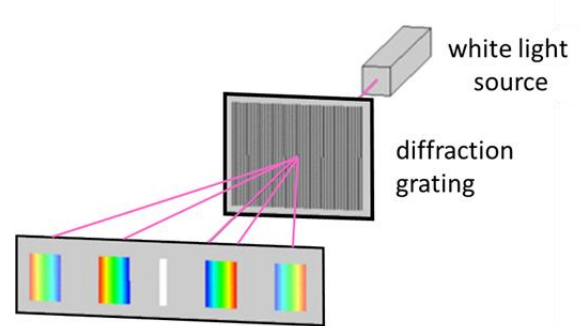


Figure 2: Diffraction grating example [4]

Once the light exits the diffraction grating, it is observed by the camera. Notice that the light is split among its spectral orders. For this experiment, the first spectral order of light is needed. To determine the angle at which the camera lies with respect to the diffraction grating, the following equation was used [2].

$$\lambda = \left(\frac{a}{k}\right) * \sin(\beta)$$

Where  $\lambda$  is the center output wavelength, 'a' is the groove spacing of the grating, 'k' is the spectral order, and  $\beta$  is the angle of the camera with respect to the grating. For the grating chosen for this project 'a' is equal to 1666.67 nm, 'k' is equal to 1 for the first spectral order, and  $\lambda$  is equal to 552.5 nm. This wavelength was chosen as it is relatively in the middle of the visible spectrum and can be shown using a green laser. With these numbers, the angle  $\beta$  is 19.36 degrees.

## Experimental Setup and Procedure

### Housing

The housing was modeled in SolidWorks 2019 and printed using the 3D printers in the Mechanical Engineering building on the University of Arkansas campus. ABS plastic was used as it was the most readily available and would print with enough quality for this application. The housing was created in two parts, an upper and lower portion. The two portions would be fit together by friction from a 2mm size lip going around most of the perimeter. This allows the assembly to be easily taken apart for maintenance and adjustments.

The first iteration was created by either measuring and creating 3D-models of the components, or using models and measurements provided by the manufacturer. These measurements and models were used to create the cuts for the components in the housing. The optical components were ensured to all be in-line with each other so the light could freely pass through without obstruction. The  $\beta$  angle of 19.36 was also incorporated into the design

between the grating and the camera lens. The lower half of the first iteration is shown in Figure 3.

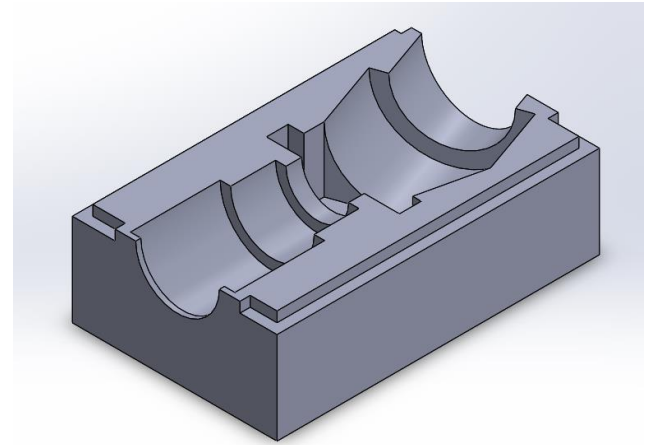


Figure 3: First iteration lower housing

This first iteration served a few purposes. It proved that the 2mm lip would work as a friction lock as the two halves could be pushed and pulled together without much effort, but also stayed together when the entire assembly is moved around. The tolerances at this first iteration proved to be too small for the components to fit snugly. Upon measuring the cuts, it appears the material shrinks slightly after printing and cooling off. The camera PCB also hangs off the back of the housing, leaving it unprotected and more prone to accidents.

The second iteration made the assembly somewhat larger, however, it added space for the camera PCB to sit inside of the housing. With the camera entirely enclosed, this reduces the wear on the camera and increases durability overall. The tolerances were also increased to allow for the shrinkage noticed at the first iteration. The lower half of the second iteration can be viewed in Figure 4.

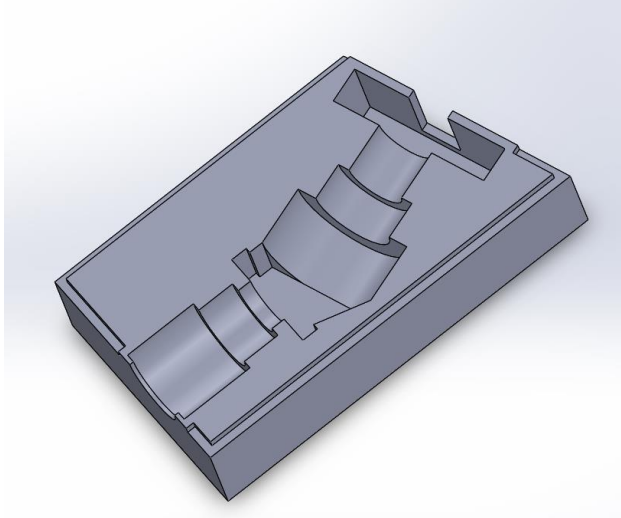


Figure 4: Second iteration lower housing

The further iterations of the housing did not see any major design changes. The tolerances of the cuts were adjusted slightly until the parts fit snug within the housing without damage occurring. Figure 5 shows the light path as it enters the optical components and through the grating. It also shows the  $\beta$  angle between the grating and camera lens.

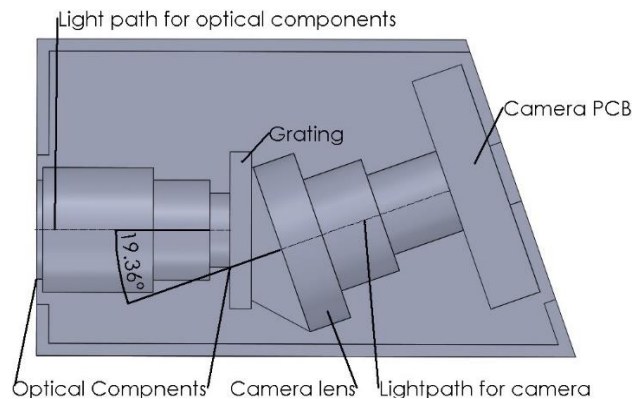


Figure 5: Angle  $\beta$  shown in final iteration.

## Off-the-shelf components

The optical components used are almost identical to the ones found in the Sigernes paper [2]. The only major change is the camera. A full parts list can be found in

Appendix A. The optical components without the camera costs about \$630 at the time of construction. All the optical components were ordered from Edmund Optics. The camera used is a small 8MP camera that interfaces via USB. This camera was chosen for its low cost and adequate resolution. This camera was ordered from Amazon. The total cost of the project, without including 3D-printed material, is under \$700.

The most important part of the optical assembly is the grating. The grating used is a 600-groove transmission grating of relatively small size, 25x25 mm, and 3 mm thick. Figure 6 shows the efficiency of different gratings with respect to wavelength.

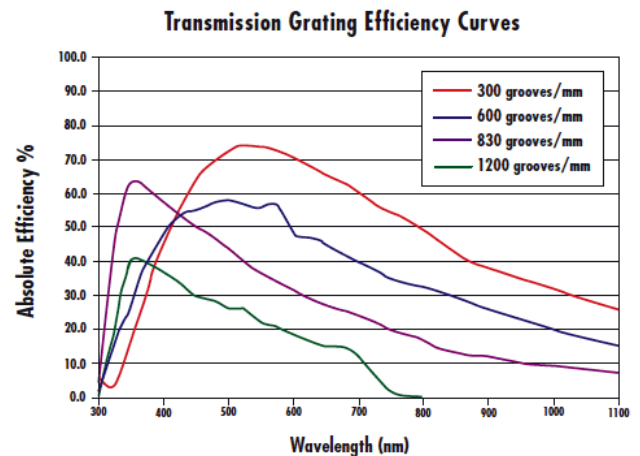


Figure 6: Transmission Grating Efficiency [Edmund Optics]

The blue line in the above figure is the line for a 600-groove grating. As seen the efficiency reaches a maximum around 550 nm. This number is in agreeance with the  $\beta$  angle calculations made for a center wavelength in the middle of the visible spectrum.

## Testing

Construction of the imager took place in Stone House on the University of Arkansas campus. The front optical assembly all mounted to each other into one unit. The transmission grating and camera are simply placed into their respective slots in the housing. Due to the delicate nature of the optical components, great care was taken during construction. The final assembly can be seen in Figure 7.



Figure 7: Final assembly

To create hyperspectral images, the exact wavelengths of the emission lines from the spectrograms must be known. The wavelength of an emission line is directly related to the position of the emission line along the x-axis of the spectrogram. By shining lasers with known wavelengths at a diffusion sheet with the imager looking at that sheet, the exact position and wavelength of that emission line is known. Doing this multiple times gives data points relating wavelength and position. This allows the creation of a trendline equation that relates the position of an emission line with its wavelength.

Three lasers were used for this application. A red laser with a wavelength of 650 nm, a green laser with a wavelength of 532 nm,

and a blue laser with a wavelength of 405 nm. These wavelengths were chosen as they represent a wide array of wavelengths across the visible spectrum. All lasers were purchased from Amazon along with the diffusion sheet. The camera was placed at a fixed distance of 15cm away from the diffusion sheet. This position was chosen as it was easy to implement into the experimental setup and gave strong emission lines. An example of the experimental setup is shown in Figure 8.

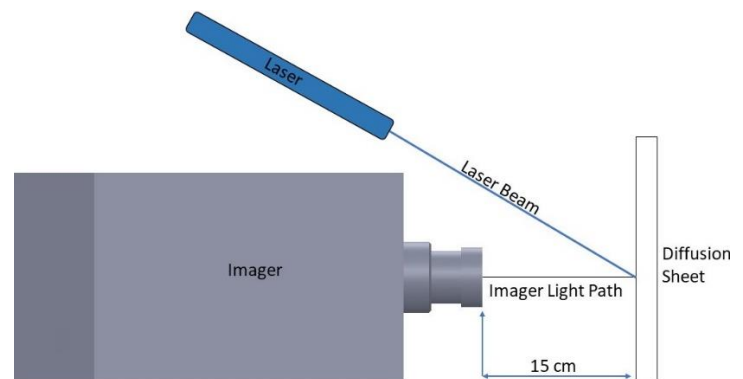


Figure 8: Experimental Setup

The imager interfaced with the built-in camera app in Windows 10 via a USB. The resolution of the images was 1920x1080 pixels. Giving a maximum pixel location of 1920 on the far right of the image. The lasers were held by hand and moved slightly until a strong emission line was observed on the computer.

With the images in hand, the pixel locations can be found with simple picture manipulation software. The pixel location for the emission line was chosen either by what appeared as the brightest portion of the emission line, or the best guess middle of the emission line. White lines were added at this location and the position of these lines were found. The processed images are seen in Figures 9-11 and the raw images can be found in Appendix B.



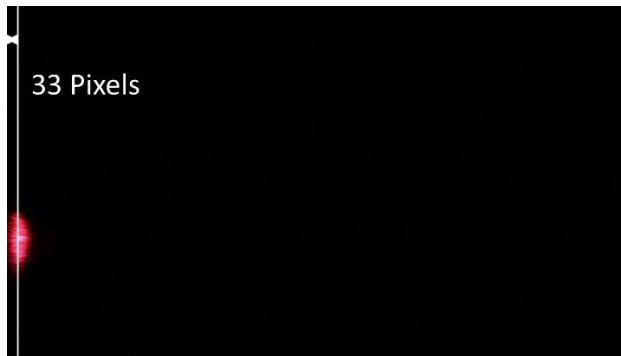


Figure 9: Red laser emission line

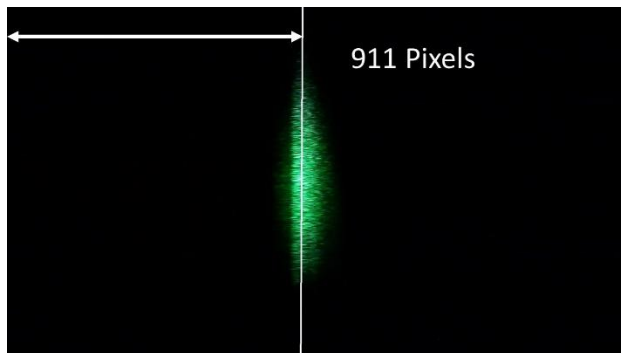


Figure 10: Green laser emission line

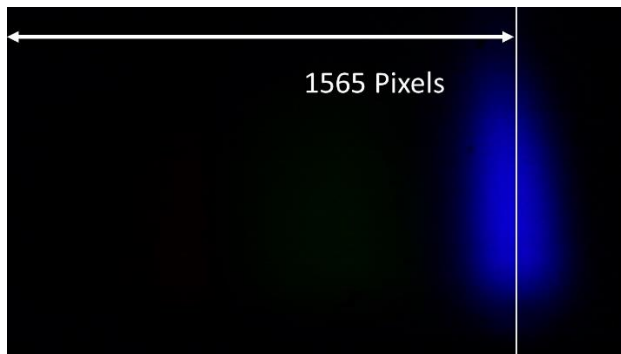


Figure 11: Blue laser emission line

Laser Color	Wavelength [nm]	Pixel
Red	650	33
Green	532	911
Blue	405	1565

Table 1: Wavelength and position data

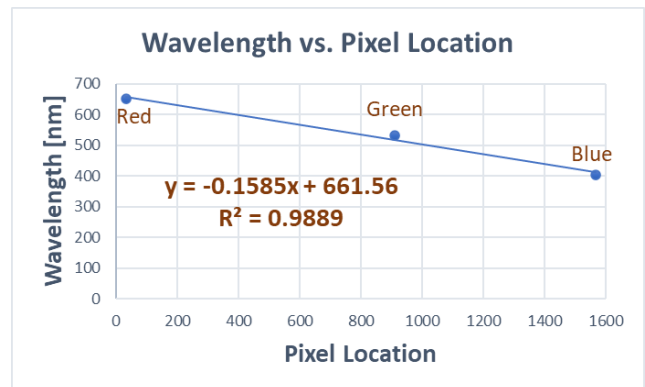


Figure 12: Plot of wavelength and pixel data

As seen here the equation has an R-squared value of 0.9889, implying a very good fit to the data. The wavelength equation is shown below:

$$\lambda \text{ [nm]} = -0.1585 * (\text{Pixel}) + 661.56$$

Where  $\lambda$  is the wavelength and 'Pixel' is the emission line location in pixels from the left-hand side of the image. Using this equation, the exact wavelength of any emission lines in the visible spectrum can be found.

## Data and Results

The processed data from the spectrograms are tabulated in Table 1. A plot of the data with wavelength on the y-axis and pixel location on the x-axis was created using Excel. From this plot a trendline and accompanying equation was added using Excel's built-in functionality, this can be seen in Figure 12.

## Future Work

In the data analysis, the red emission lines with the longest wavelengths are shown on the left of the image, and the blue emission lines with the shortest emission lines are on the right side. This is the opposite of what was expected. Normally spectrograms show longer wavelengths farther to the right and shorter on the left. This is ultimately due to

the position of the camera with respect to the grating. Figure 13 below shows again how this diffraction grating splits the incoming light.

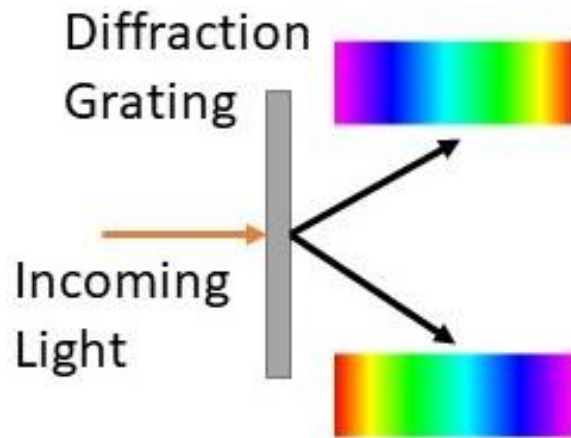


Figure 13: Diffraction Grating

Figure 14 shows how the camera is currently set up with respect to the grating. As seen here the light the camera is detecting is flipped with red on the left and blue on the right.

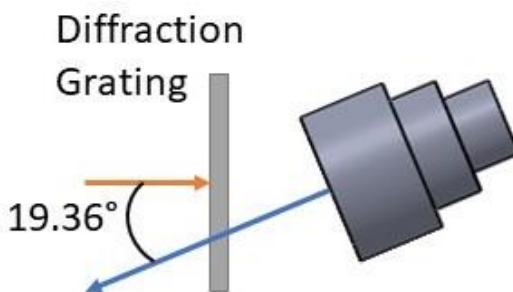


Figure 14: Current camera setup

To correct this issue, the camera should be moved with respect to the grating to the position shown in Figure 15. This will ensure the light entering has red on the right and will mitigate any unforeseen errors as the current setup is not how it was intended to be used.

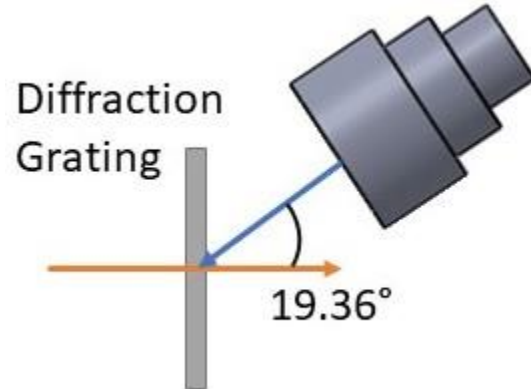


Figure 15: Proposed camera setup

There is still much work to be done to create actual hyperspectral images. With the above change made to the housing, the entire imager needs to be calibrated again and a new equation formed. A soft lining around where the grating sits in the housing should also be considered. The grating is very delicate and is susceptible to scratches from the ABS plastic. A lining made of felt or other available materials should be attached to the inside of the housing.

Beyond that, a major milestone will be advancing this imager to be useful in the infrared and near-infrared spectra. An entirely new camera will likely need to be made using optical components suited for those spectra.

## Conclusions

Modern 3D-printing and the availability of optical components can lead to a working camera able to create spectrograms which hyperspectral images can be created from. The total cost for such a camera is under \$1000 depending on the equipment used.

This project was primarily conducted by Joshua Moorhouse and Connor Heo. Joshua Moorhouse's responsibilities included the

design and printing of the housing, construction, and data acquisition. Connor Heo's responsibilities included procurement, testing configuration, and data analysis. Brandon Wallace was brought onto the project as Joshua Moorhouse and Connor Heo left the project and is currently working on advancing the project into the infrared and near-infrared spectra.

## References

- [1] "Hyperspectral Systems Increase Imaging Capabilities," *NASA*. [Online]. Available: [https://spinoff.nasa.gov/Spinoff2010/hm\\_4.html](https://spinoff.nasa.gov/Spinoff2010/hm_4.html). [Accessed: 03-Apr-2020].
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- [4] *VISUAL PHYSICS ONLINE*. [Online]. Available: [http://www.physics.usyd.edu.au/teach\\_res/hsp/sp/mod31/m31\\_Grating.htm](http://www.physics.usyd.edu.au/teach_res/hsp/sp/mod31/m31_Grating.htm). [Accessed: 03-Apr-2020].

## Appendix A:

### Full Parts List

Part	Part Number (EO)
Front lens f/4 Focal Length (FL) 16 mm	83-107
M12 lock nut for $\mu$ -video lenses	64-102
Precision air slit 25 $\mu$ m x 3mm	38-558
Field lens FL = 10 mm	63-519
3 x S-Mount thin lens mounts	63-943
S-mount focus tube	63-953
Collimator lens FL = 30 mm	63-523
600 grooves/mm transmission grating 25 x 25 mm <sup>2</sup>	49-580
Detector lens f/2.5 FL = 25 mm	56-776
S-Mount brass spacer rings	54-461
C-mount to $\mu$ -video lens adapter	53-675

Part	Description
Detector	Spinel 8MP USB Camera UC80MPA_ND
3-Pack Lasers	Bedoo 3-Pack Red, Green, Blue Lasers
Diffusion Sheet	Neewer 12x5ft Nylon Silk White Diffusion Fabric

## Appendix B:

### Raw Spectrograms



Figure B.1: Red laser, raw image

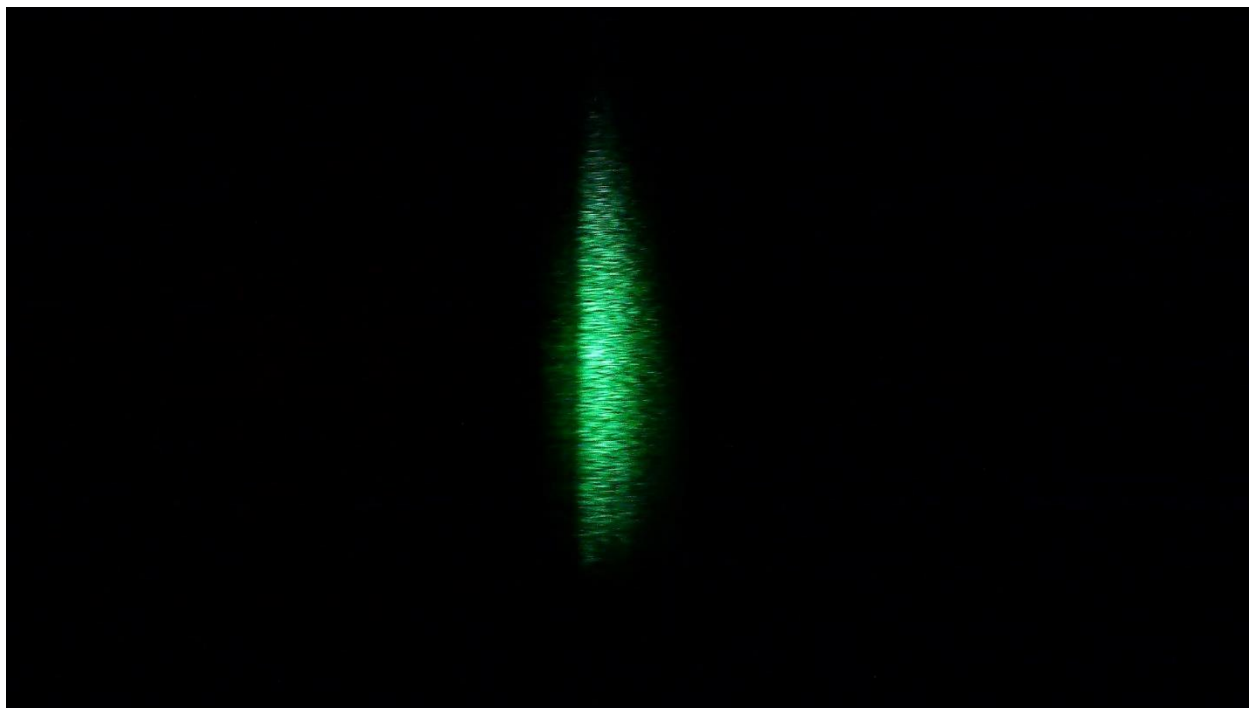


Figure B.2: Green laser, raw image



Figure B.3: Blue laser, raw image